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Implications Of A Non-Standard Light Higgs Boson

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Abstract

Analyses of the vacuum stability of the electroweak theory indicate that new physics occur at a scale of order of 1 TeV if a light Higgs is discovered at LEP II. In this paper, we parameterize the effects of new physics in the effective Lagrangian approach and examine its implication on the Higgs boson production at LEP II. We consider the effect of higher dimension operator on the Higgs potential and calculate the lower bound on the Higgs boson mass from the requirement of vacuum stability. We show that if a Higgs boson is seen at LEP II then under favourable conditions the deviation of the production cross section from the standard model value could be significant and therefore the presence of the new physics is detectable at LEP II.

1 Introduction

One of the important issues in particle physics is to understand the origin of the electroweak scale. In the standard model, the electroweak symmetry breaking arises from a complex fundamental Higgs scalar. However, the theoretical arguments of "triviality" [1] and "naturalness" [2], suggest that such a simple spontaneous symmetry breaking mechanism may not be the whole story. This leads to the belief that the Higgs sector of the standard model is an effective theory. The advent of new physics which reveals a more fundamental structure underlying the symmetry breaking mechanism can be defined by an energy scale Λ which also serves as a cutoff of the effective theory.

As a requirement of the Higgs sector, the effective potential should have a global minimum at the electroweak scale ($v = 246\text{GeV}$). This is the condition of vacuum stability[3]. For the existence of a light Higgs boson, within the energy range of LEP II, the standard model vacuum will become unstable at the order of 1 TeV, because of the large destabilizing effect of the top quark contribution to the effective potential. This can be taken as an indication of the presence of new physics around this scale. With such a low cutoff one expects effects of new physics to show up relatively soon, even in experiments at LEP II.

There are various proposals of new physics beyond the standard model, such as SUSY, Left-Right models, multi-Higgs models, composite Higgs models, Top quark condensation models, etc. Recently Hung and Sher [4] has studied the question of vacuum stability in a specific model with a singlet scalar added to the standard model. In this paper we consider a model independent approach to new physics, *i.e.*, the effective Lagrangian approach, and analyze the implication of vacuum stability on the Higgs boson mass and its production. Our analysis show that, if the Higgs boson is discovered at LEP II then the scale of new physics should be around $\mathcal{O}(1\text{ TeV})$, and the new physics effects on the Higgs production can be sizable. For instance, for a Higgs of mass of 75 GeV, the correction to the cross section for $e^+e^- \rightarrow ZH$ due to new physics can be around 8–11%,

which is detectable at LEP II.

This paper is organized as follows: in Section 2, we analyze the Higgs boson mass bound in the effective theory. In Section 3, we discuss the possible effects of new physics on Higgs boson production at LEP II and in Section 4, we briefly summarize our results.

2 Effective theory and Higgs mass bound

In the effective Lagrangian approach to new physics, the leading terms are given by the standard model. The corrections which come from a certain underlying theory beyond the standard model are described by higher dimension operators,

$$\mathcal{L}^{new} = \sum_i \frac{c_i}{\Lambda^{d_i-4}} \mathcal{O}^i, \quad (1)$$

where d_i are the dimensions of \mathcal{O}^i , which are integers greater than 4. The operators \mathcal{O}^i are $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant and contain only the standard model fields. The dimensionless parameters c_i , determining the strength of the contribution of operators \mathcal{O}^i , can be calculated by matching the effective theory with the underlying theory. In general, if the new physics is due to a strongly interacting system, for instance in a composite Higgs model [5] or with a low scale top condensate models [6], c_i are expected to be of $O(1)$. For weakly coupled new physics the parameters c_i may be an order of magnitude smaller.

Analyses of higher dimension operators have been performed by many authors [7]. In this paper we consider only CP conserving operators which can be constructed out of the Higgs fields Φ , covariant derivatives of the Higgs field, $D_\mu \Phi$, and the field strength tensors $W_{\mu\nu}$ and $B_{\mu\nu}$ of the $SU(2)$ and the $U(1)$ gauge fields. There are 8 dimension-six operators denoted by $\mathcal{O}_{\Phi,1}, \mathcal{O}_{\Phi,2}, \mathcal{O}_{BW}, \mathcal{O}_W, \mathcal{O}_B, \mathcal{O}_{WW}, \mathcal{O}_{BB}$ and $\mathcal{O}_{\Phi,3}$. They modify the standard model Lagrangian to the $1/\Lambda^2$ order and the effective Lagrangian for new physics, \mathcal{L}^{new} , up to dimension 6, is given by

$$\mathcal{L}^{new} = \frac{1}{\Lambda^2} c_{\Phi,3} \left(\Phi^+ \Phi - \frac{v^2}{2} \right)^3$$

$$\begin{aligned}
& + \frac{1}{\Lambda^2} \left[c_{\Phi,1} (D_\mu \Phi)^+ \Phi \Phi^+ (D^\mu \Phi) + \frac{1}{2} c_{\Phi,2} \partial_\mu (\Phi^+ \Phi) \partial^\mu (\Phi^+ \Phi) \right] \\
& + \frac{1}{\Lambda^2} \left[c_{BW} \Phi^+ \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi + c_W (D_\mu \Phi)^+ \hat{W}^{\mu\nu} (D_\nu \Phi) \right] \\
& + \frac{1}{\Lambda^2} \left[c_B (D_\mu \Phi)^+ \hat{B}^{\mu\nu} (D_\nu \Phi) + c_{WW} \Phi^+ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \right] \\
& + \frac{1}{\Lambda^2} c_{BB} \Phi^+ \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi. \tag{2}
\end{aligned}$$

Only $\mathcal{O}_{\Phi,3}$ contributes to the effective Higgs potential. All the other operators except $c_{\Phi,3}$ will contribute to the Higgs boson production and in Section 3 we will study the effect of these operators in Higgs boson production.

In the presence of the higher dimensional operator $\mathcal{O}_{\Phi,3}$ the tree level Higgs potential can now be written as

$$V_{tree} = -\frac{m^2}{2} \phi^2 + \frac{1}{4} \lambda \phi^4 + \frac{1}{8} \frac{c_{\phi,3}}{\Lambda^2} (\phi^2 - v^2)^3, \tag{3}$$

which is corrected by the one-loop term, V_{1loop} ,

$$V_{1loop}(\mu) = \sum_i \frac{n_i}{64\pi^2} M_i^4(\phi) \left[\log \frac{M_i^2(\phi)}{\mu^2} - C_i \right], \tag{4}$$

where

$$\begin{aligned}
M_i^2(\phi) &= k_i \phi^2 - k'_i. \\
\tag{5}
\end{aligned}$$

The summation goes over the gauge bosons, the fermions and the scalars of the standard model. The values of the constants n_i , k_i , k'_i and C_i can be found in Refs[3, 8]. The one-loop effective potential, including the higher dimensional operators, is

$$V = V_{tree} + V_{1loop}.$$

In Fig.(1) we plot the effective potential for $\Lambda = 4$ TeV and for three typical values of $c_{\phi,3}$. We see that the effect of a positive $c_{\phi,3}$ is to delay the onset of vacuum instability compared to the standard model while the effect of a negative $c_{\phi,3}$ is to accelerate the onset of vacuum instability.

To obtain a lower bound on the Higgs boson mass, in the absence of higher dimensional operators one can take the location of vacuum instability to be as large as Λ . However, in our approach, for the low energy theory to make sense, we should require $\phi < \Lambda$. We take the scale of vacuum instability, Λ' , to be 0.5Λ , so the corrections from operators of dimension greater than six to our result is suppressed by a factor of $\frac{\Lambda'^2}{\Lambda^2} = 0.25$. In Fig. (2) we plot the lower bound of the Higgs mass versus Λ .

Since we are dealing with values of the field ϕ larger than v , we need to consider a renormalization group improved potential for our analysis [3, 8, 9, 10, 11, 12]. Working with the one-loop effective potential, we consider two-loop running for λ , the top Yukawa coupling (g_Y), gauge couplings and the Higgs mass. This procedure resums all next-to-leading logarithm contributions [13]. The various β functions to two-loop order can be found in Ref [14]. After obtaining the running Higgs boson mass, the physical pole mass ¹ can be calculated. The relevant equation relating the running mass to the pole mass can be found in Ref [8]. The boundary conditions for the gauge couplings and the top quark Yukawa couplings are known at the electroweak scale in terms of the measured values, taking into account the connection between the running top mass and the pole top mass measured at 175 GeV. The vacuum stability requirement provides the boundary condition for λ at the scale Λ' , which is given by

$$\lambda_{eff}(\Lambda') \approx - \sum_i \frac{n_i}{16\pi^2} k_i^2 (\log k_i - C_i) - \frac{1}{2} \frac{\Lambda'^2}{\Lambda^2} c_{\Phi,3}, \quad (6)$$

where

$$\lambda_{eff}(\Lambda') = \lambda(\Lambda') - \frac{3}{2} c_{\Phi,3} \frac{v^2}{\Lambda^2}. \quad (7)$$

In Fig. (3) we show the renormalization group improved Higgs mass bound versus Λ . We see that for a light Higgs mass within the discovery range of LEPII, the new physics scale is a few TeV. For

¹ The effect of the operator $c_{\Phi,2}$ in Eq. (2) causes an finite renormalization of the Higgs field H [7]. $H \rightarrow Z_H^{\frac{1}{2}} H$, where $Z_H^{-1} = 1 + c_{\Phi,2} \frac{v^2}{\Lambda^2}$. This gives rise to a correction to the Higgs boson mass by $\sim 2\%$ for $c_{\Phi,2} \sim O(1)$.

$c_{\Phi,3} = 1.0$ the higher dimensional operator helps to significantly stabilize the vacuum to such an extent that the scale of new physics will be too large to show any significant effect at LEP II.

3 Higgs Boson Production

In Section 2, we have considered the Higgs mass bound that stabilize the electroweak vacuum in the effective theory. Turning the argument around we can see from Fig. (3) that if the Higgs boson is found at LEP II then we can read off the upper bound for the scale of new physics. As an example, with $c_{\Phi,3} = -1.0$ and $m_H = 75$ GeV the new physics scale is $\lesssim 1.08$ TeV. This is perhaps as much as can be said about the effect of the operator $O_{\Phi,3}$. However the presence of the other operators in Eq.(2) will modify the couplings of the Higgs boson interactions. The determination of a low scale for new physics will allow the effects of the other operators to manifest themselves more readily. In this section we will show that under favourable conditions new physics effects can be visible at LEP II and the mechanism of new physics, strong versus weakly interacting may also be discernible. We expect this new physics effect to manifest in the Higgs production, $e^+e^- \rightarrow ZH$ ² at LEP II. The Lagrangian given in Eq.(2) gives rise to anomalous Higgs couplings, which can affect Higgs boson production. Following Ref[7] we write down the relevant vertices generated from the Lagrangian in Eq. (2) in terms of the physical Higgs field, H .

$$\mathcal{L}_{eff} = \frac{gM_W}{\Lambda^2} [T_1 H Z_\mu Z^\mu + T_2 Z_{\mu\nu} Z^\mu (\partial^\nu H) + T_3 H Z_{\mu\nu} Z^{\mu\nu} + T_4 A_{\mu\nu} Z^\mu (\partial^\nu H) + T_5 H A_{\mu\nu} Z^{\mu\nu}], \quad (8)$$

with

$$\begin{aligned} T_1 &= \frac{2m_W^2 c_{\Phi,1}}{g^2 c^2}, \\ T_2 &= \frac{c^2 c_W + s^2 c_B}{2c^2}, \\ T_3 &= -\frac{c^4 c_{WW} + s^4 c_{BB} + s^2 c^2 c_{BW}}{2c^2}, \end{aligned}$$

² This process has recently received attention as a probe for new physics at LEP II [15].

$$\begin{aligned} T_4 &= \frac{s(c_W - c_B)}{2c}, \\ T_5 &= \frac{s(-2c^2 c_{WW} + 2s^2 c_{BB} + (c^2 - s^2)c_{BW})}{2c}, \end{aligned}$$

where $g^2 = e^2/s^2 = 8m_W^2 G_F/\sqrt{2}$ and s and c are the sine and cosine of the Weinberg angle.. We also include the effects of the Higgs boson wavefunction renormalization due to operators $\mathcal{O}_{\Phi,1}$ and $\mathcal{O}_{\Phi,2}$,

$$\mathcal{L}_{ren} = \frac{1}{2}g_Z M_Z \left[1 - \frac{c_{\Phi,1} + c_{\Phi,2}}{2} \frac{v^2}{\Lambda^2} \right] H Z_\mu Z^\mu. \quad (9)$$

The strength of the anomalous Higgs couplings depends on the values of various coefficients c_i . In a strongly interacting theory for the Higgs sector, such as composite Higgs boson models[5] and low scale top condensation models[6], it is difficult to calculate the absolute values of c_i . However, one expects in general that $c_i \sim \mathcal{O}(1)$ ³. In Fig. (4) we show the cross sections for the process $e^+e^- \rightarrow ZH$ for $c_i \sim 0(1)$. The formula for the cross sections can be found in Ref[15].

We see that new physics effects are at a level of

$$R = \frac{\sigma_{NSM} - \sigma_{SM}}{\sigma_{SM}} = 8 - 11\%,$$

where σ_{SM} is the standard model cross section and σ_{NSM} is the cross section with the inclusion of anomalous couplings⁴. In LEP II with a center of mass energy 175-205 GeV and an integrated luminosity of $300 - 500 pb^{-1}$ new physics effects on the Higgs boson production with the magnitude

³ Operator $\mathcal{O}_{\Phi,1}$ contributes to the ρ parameter and is therefore tightly constrained. We set $c_{\Phi,1} = 0$ in our calculation by assuming the existence of a custodial $SU(2)$ in these models. The coefficients of the other operators are taken to be $\mathcal{O}(1)$. The operator \mathcal{O}_{BW} contributes to the S parameter of Peskin and Takeuchi. For our choice of the new physics scale given above the correction of the operator \mathcal{O}_{BW} to S is ~ -0.6 which is within the experimental limit on S [16].

⁴ We have not included radiative corrections to the cross section because they are known to be small at LEP energies [17] and the percentage change to cross section with or without anomalous couplings due to radiative corrections will approximately be equal. The ratio R , therefore, will remain almost the same with or without radiative corrections.

mentioned above will be detectable[18]. However if the new physics is weakly interacting, c_i may be of the order of 0.1 or smaller, then the correction to the Higgs production cross section will be too small to be visible at LEP II.

4 Summary

In summary, we have re-examined the Higgs mass bound from the requirement of vacuum stability in the effective theory by taking into account the contribution of higher dimension operators to the effective potential⁵. We show that if the Higgs boson is discovered at LEP II, new physics could be around TeV and its effect on Higgs boson production will be observable at LEP II in certain models with strong interaction as the underlying dynamics of the Higgs sector.

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⁵ High dimension operator correction to the effective potential for electroweak baryogenesis was considered in [19].

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5 Figure Captions

Fig. 1 The effective potential for various values of $c_{\phi,3}$. The Higgs mass is taken as $80GeV$ and the scale of new physics $\Lambda = 4TeV$. The curve with $c_{\phi,3} = 0$ corresponds to the standard model.

Fig. 2 The lower bound on the Higgs mass as a function of the new physics scale Λ . The scale of vacuum stability has been chosen to be $\Lambda' = \frac{\Lambda}{2}$. The scale in the effective potential is set at $\mu = v = 246GeV$.

Fig. 3 The lower bound on the Higgs mass as a function of the new physics scale Λ for various $c_{\phi,3}$. The scale of vacuum stability has been chosen to be $\Lambda' = \frac{\Lambda}{2}$. A renormalization group improved effective potential has been used and the running of the couplings in the potential have been considered up to two loop order.

Fig. 4 The cross section for $e^+e^- \rightarrow ZH$ for a Higgs mass of $75GeV$ in the standard model and including anomalous couplings.

Fig. 1

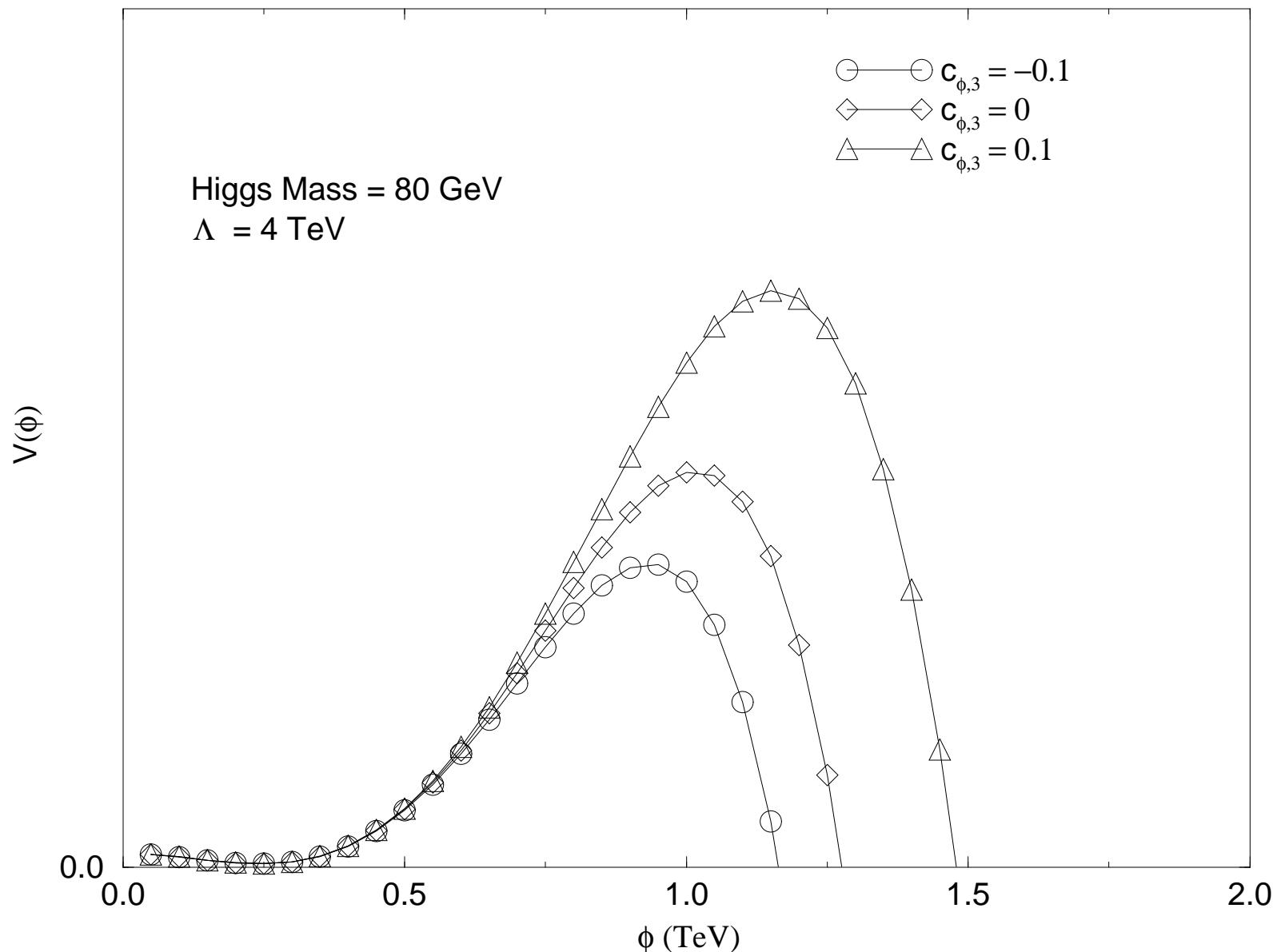


Fig. 2

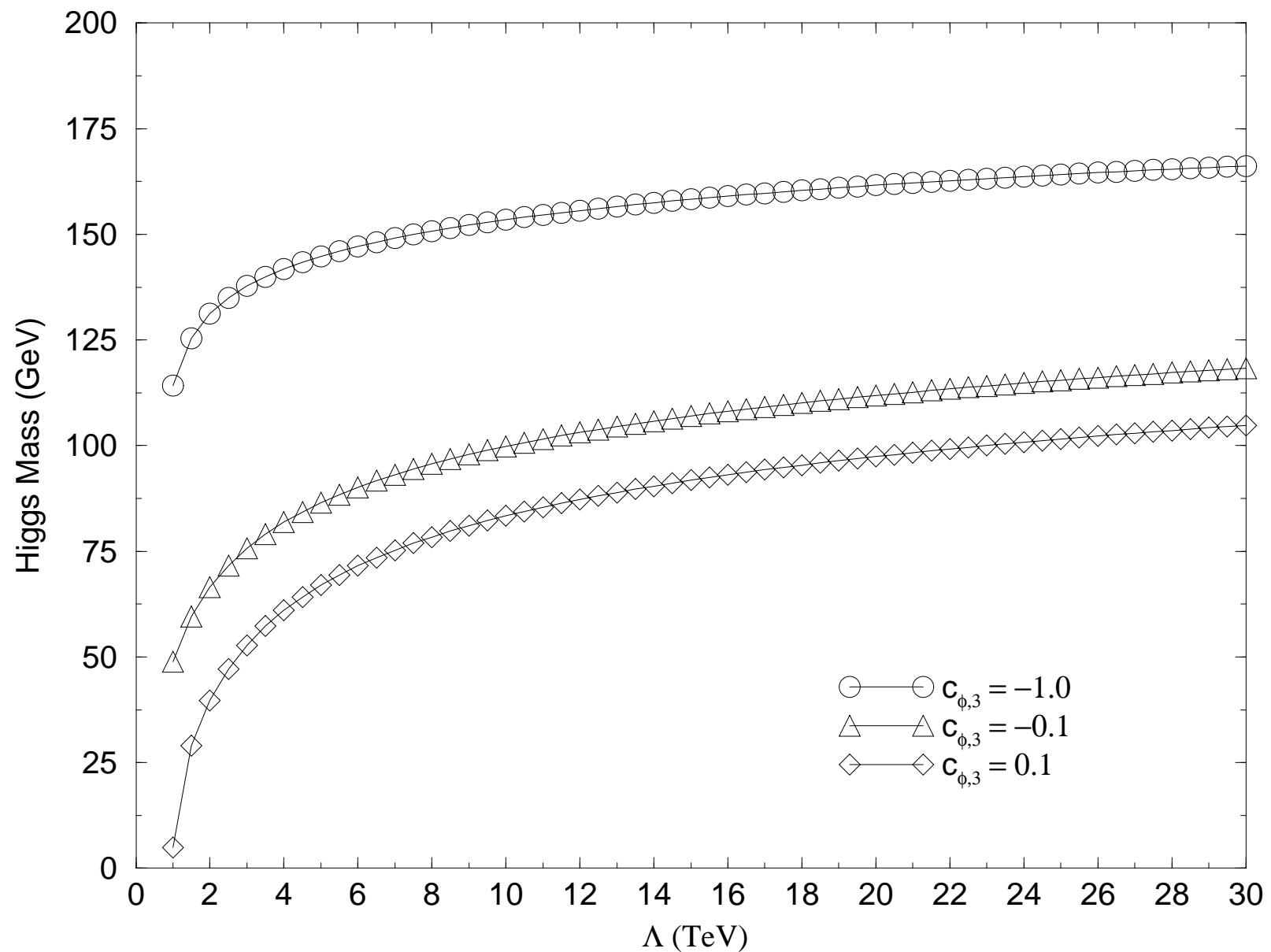


Fig. 3

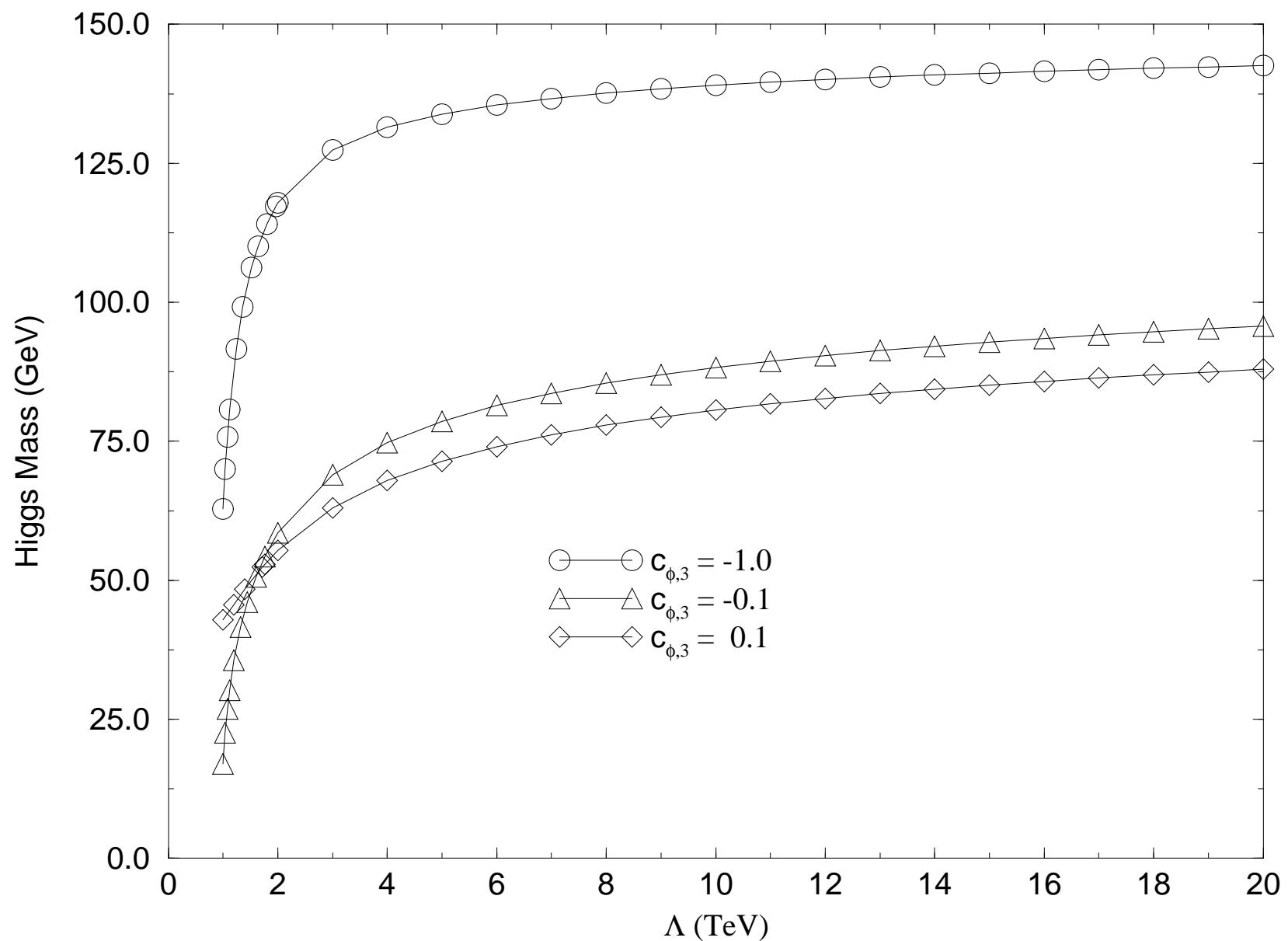


Fig. 4

